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Acoustic Emission: Some Applications of Lamb's Problem

Franklin R. Breckenridge, Carl E. Tschiegg and Martin Greenspan

Sound Section
Mechanics Division
Institute for Basic Standards
National Bureau of Standards
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Final

Report to
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ABSTRACT

A method for obtaining the signatures (waveforms) of certain acoustic emission events has been developed. The waveform is that at the source, free of contamination by ringing of the specimen, apparatus and transducer. The technique is based on the comparison of two signals at the transducer, one from the event in question and one from an artificial event of known waveform. The apparatus is also adapted to the calibration of transducers in a certain sense. The configurations of source (real or simulated acoustic-emission event) and receiving transducer correspond to those of some special cases of Lamb's problem. As a byproduct, the results may be of some interest to seismologists.

Key Words: Acoustic emission; calibration of transducers; electrostatic transducers; Lamb's problem; seismic pulses; ultrasonic transducers.

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INTRODUCTION

It is widely thought, or at least hoped, that the waveform (or the spectrum) of an acoustic emission signal is characteristic of the process which produces it (the source event), and considerable effort has been expended in attempts to obtain such in the laboratory.[1,2,3] So far, no really satisfactory waveforms have been acquired. There are two main difficulties. The first, which is the requirement for a wide-band transducer, with a consequent loss of sensitivity, can be set aside for the present if attention is directed only to sufficiently energetic events. The second is more troublesome. The source event excites the test specimen, and frequently the testing apparatus, into vibration (ringing), masking the desired signal. That is, the spectrum of the signal for the most part reflects merely the normal modes of vibration of the specimen and apparatus.

We describe some apparatus which is expected to circumvent the above difficulty, at least in considerable part. However, it develops that the same apparatus, with only minor modifications, can be used in the calibration of acoustic-emission transducers, and we now report on this phase of the work. We also present some results of interest to seismologists.

PRINCIPLE OF THE METHOD

Figure 1 is a schematic of the basic apparatus. The "transfer block", A, is a thick slab of aluminum alloy, steel, glass or other material having low attenuation for sound in the megahertz range. The test specimen, B, coupled to the transfer block sometimes through a liquid or a grease, should be no larger than a few tenths of a millimetre in any dimension. When the sample is deformed by the threaded indenter, C, acoustic emissions take place, usually one at a time because of the samll volume of the sample. The signal from each event is picked up by a transducer, D, directly opposite the specimen. The transverse dimensions of the transfer block are large enough so that the first reflections from the lateral walls arrive at the transducer too late to interfere with the reception of the important part of the signal. The effects of ringing of the block are thus avoided. The specimen is small, and it therefore rings only at frequencies above the range of interest. Thus it appears possible, in a research situation, to obtain a signal from a source event uncontaminated by ringing of the specimen. Of course, in practice, the event usually occurs somewhere in the interior of a solid, rather than on a surface, but we shall later present some evidence that this point is not too important.

If we knew the response of the transducer, and the transfer function of the block, we could calculate from the received signal the signature of the source event at its point of origin. Here it is well to digress and consider what is meant by the response of the

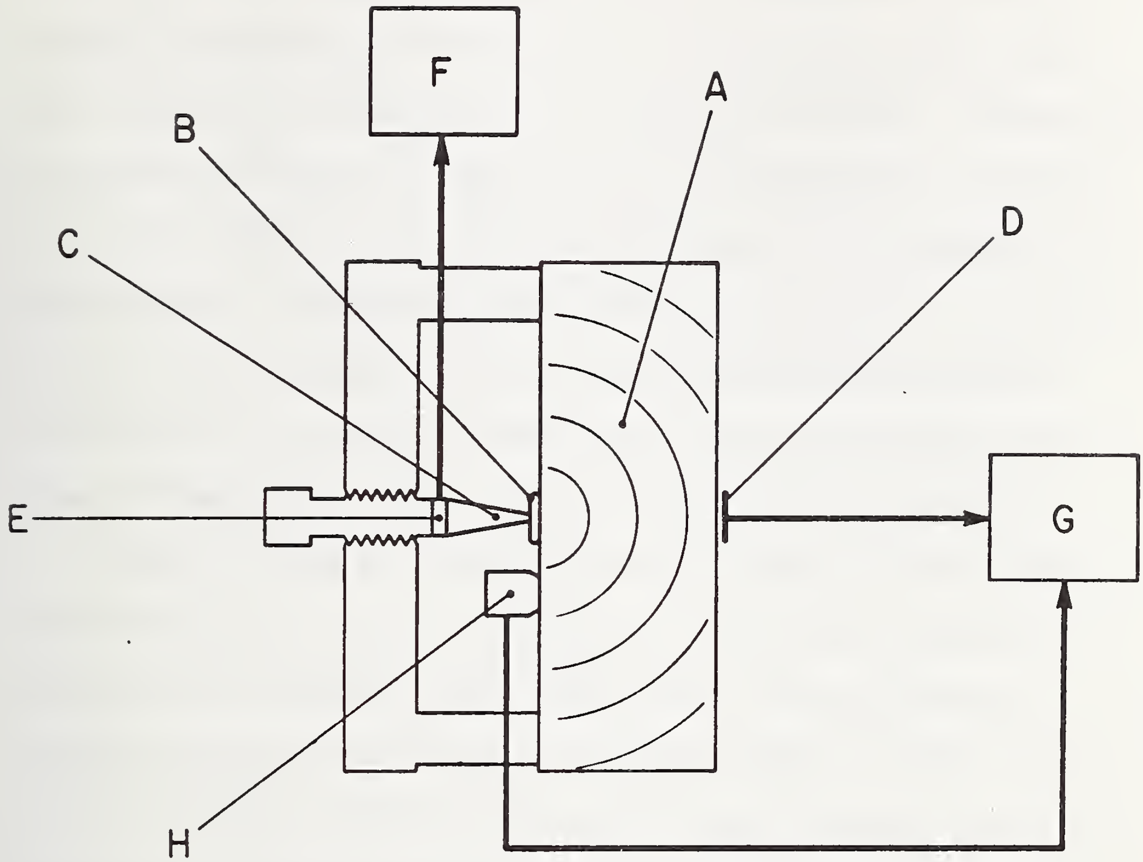

FIG. 1. Schematic of set-up for recording of acoustic-emission signatures uncontaminated by ringing of specimen: A, transfer block; B, test sample; C, indenter; D, transducer; E, lead zirconate-titanate disc; F, charge amplifier; G, high-speed storage oscilloscope; H, trigger-signal pickup.

transducer. In acoustic emission work, the transducer is usually thought of as measuring stress, but it is placed on a free surface where there is no traction when the transducer is absent. Whatever the transducer is supposed to measure, stress, displacement or velocity, its output depends on the impedance it presents to the specimen, and this depends on frequency, usually in a complicated way. Transducers which are not in contact with the specimen, and perforce measure displacement or velocity, are exceptions, and we will discuss them later. However, they have in general relatively low sensitivity.

Thus, in trying to implement the above scheme, we are faced with two difficulties. For one, we do not know under what conditions to calibrate the transducer, and for the other, we do not know the transfer function of the block. It seems desirable to bypass these problems and take a different approach. Suppose that we produce, at the point on the surface of the transfer block at which the specimen normally is put, a stress pulse having a known waveform and therefore a known spectrum. We create thus a "standard source event" and record at the transducer output a "standard signal", different for different transducers. Then from the spectrum of the test signal and that of the standard signal as measured on the same transducer, and the known spectrum of the standard source event, the spectrum of the test source event at its point of origin can be calculated.

STANDARD SOURCE EVENT AND STANDARD RECEIVER

We have chosen for the standard source event a step function of stress. To realize it, a short length of thin-walled glass capillary, of diameter about 0.15 mm, is substituted for the specimen, B, in Fig. 1 and slowly compressed by means of the threaded indenter, C, until it breaks. Upon fracture, the load is released suddenly; we shall see that the rise time (10-90 percent) is less than 0.1 μs. A disc of lead zirconate-titanate, E, connected to a charge amplifier, F, can be used to measure the total load released (of the order of 10 N); it is calibrated with dead weights.

In order to establish an upper limit on the rise time of the step-function load produced by breaking a capillary, we need an elastic system, having a known transfer function, of which the step-function is the input, and a transducer, which does not load the system, for an output. For the latter we have chosen a D.C.-biased electrostatic transducer. Such transducers have been used as transmitters and receivers for high-frequency sound in solids for many years, beginning perhaps with Bordoni and Nuovo[4] (who, however, tuned them by means of inductors to produce a small bandwidth and high sensitivity), and continuing up to recent work by Legros, et. al.[5] and by Graham and Alers.[2] In these cases, and all others we know about, except for some work by Sherwood,[6] solid dielectrics (thin plastic films) were employed, metallized on one side to provide the outer electrode. We find these to have

undesirable resonances. A massive outer electrode, with either solid or air dielectric is much better. In many ways, air-dielectric transducers are more satisfactory; although use of solid dielectric increases the sensitivity it usually introduces anomalous frequency effects and instabilities associated with humidity and perhaps other variables.

A little reflection will show that in the ideal case, an air-dielectric transducer should be flat with frequency as a force transmitter or as a displacement receiver. (The differentiated output should be flat with velocity.) In a practical case the resonant properties of the air gap must be considered. The acoustical impedance of the air gap as seen at the surface of the transfer block will be high near zero frequency and near frequencies for which the gap is a multiple of a half wavelength. In our case a typical thickness of air gap is about 4 μm (set by small shims of polycarbonate film) for which the lowest antiresonant frequency is about 40 MHz. A simple calculation shows that the impedance of the air gap will be less than 5 percent of the characteristic impedance of a typical solid for frequencies ranging from about 6 kHz to just below 40 MHz. This calculation ignores the attenuation in the air and air pumping at low frequencies, but it is clear that we can expect our transducers to have a very large bandwidth, and experiment bears this out. We also find that an increase in the mass of the outer electrode lowers the lower cutoff frequency, so it is likely that this cutoff is set by resonance of the mass of the electrode

with the compliance of the shims. To use an air gap as small as 4 μm with a polarization of some 250 V successfully requires that the opposing surfaces be scraped flat and smooth, and that scrupulous cleanliness be observed during assembly.

A SEISMIC SURFACE PULSE EXPERIMENT

To check on these ideas, we examine the following problem, borrowed from seismology. A step-function of force, $ZU(t)$, is applied at a point on, and normal to the plane surface of a semi-infinite isotropic solid for which the speed of the shear wave is c and the shear modulus is μ. The vertical displacement of the surface, w, is measured at a distance r. This problem was first studied by Lamb[7] and since then by many others. We use explicit expressions given by Pekeris.[8] It turns out that $w\pi\mu r/Z$ is a function only of $\tau = ct/r$. Pekeris presents the result for Poisson's ratio, υ, equal to 1/4, numerically the simplest case. The result is shown in Fig. 2, to which we may compare an oscillogram, Fig. 3, taken on a glass plate for which the measured value of υ was 0.226. Figure 4 shows the result of a calculation we have made[9] for the case $\upsilon = 1/3$, and Fig. 5 is an oscillogram taken on an aluminum-alloy block for which the measured value of υ was 0.343. The differentiated output, proportional to velocity, is shown on the oscillogram, Fig. 6. The apparatus (aluminum block) is shown in the photograph, Fig. 7. In these experiments the loads were applied using breaking glass capillaries as described, and the displacements

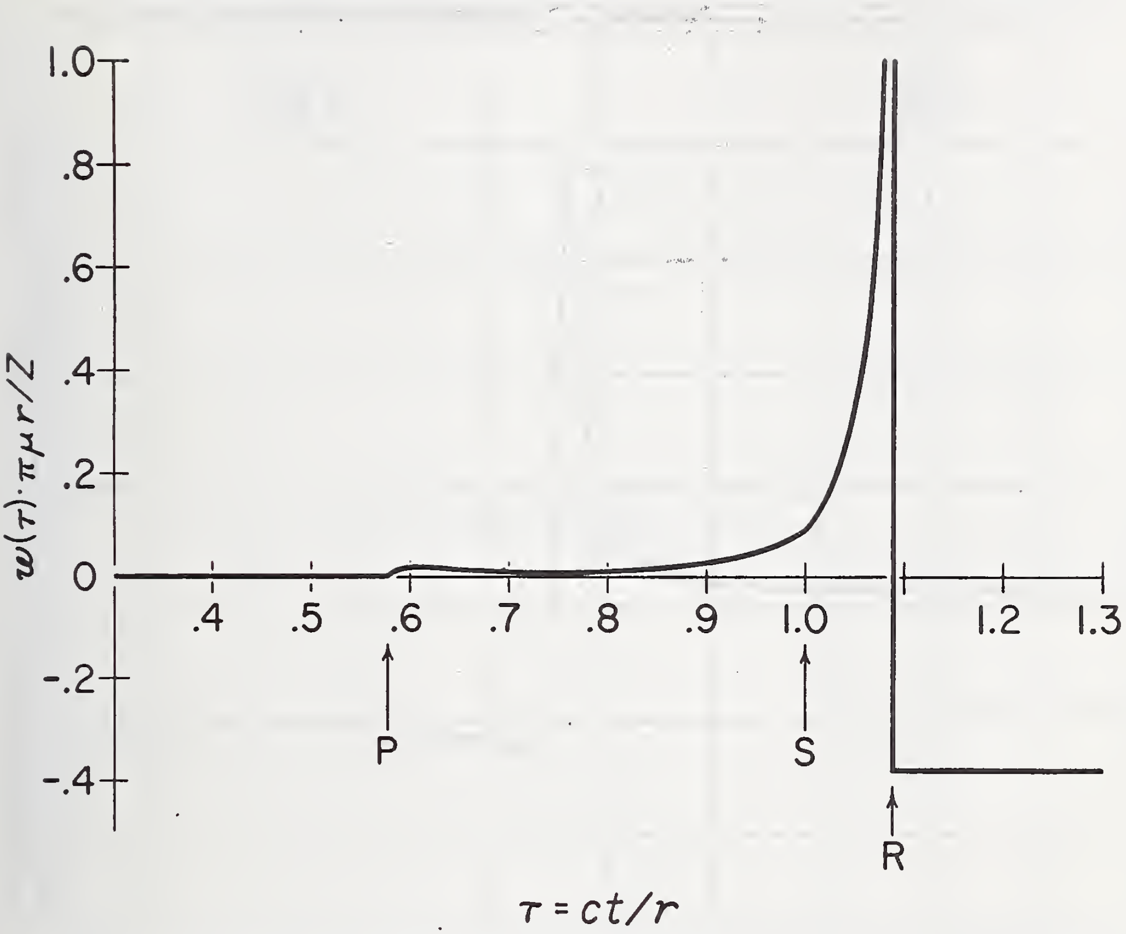

FIG. 2. Vertical displacement for seismic surface pulse calculated from an expression of Pekeris[8] for $\nu = 1/4$. P, S, and R show arrivals of the longitudinal, shear, and Rayleigh waves, respectively. See text for meaning of symbols.

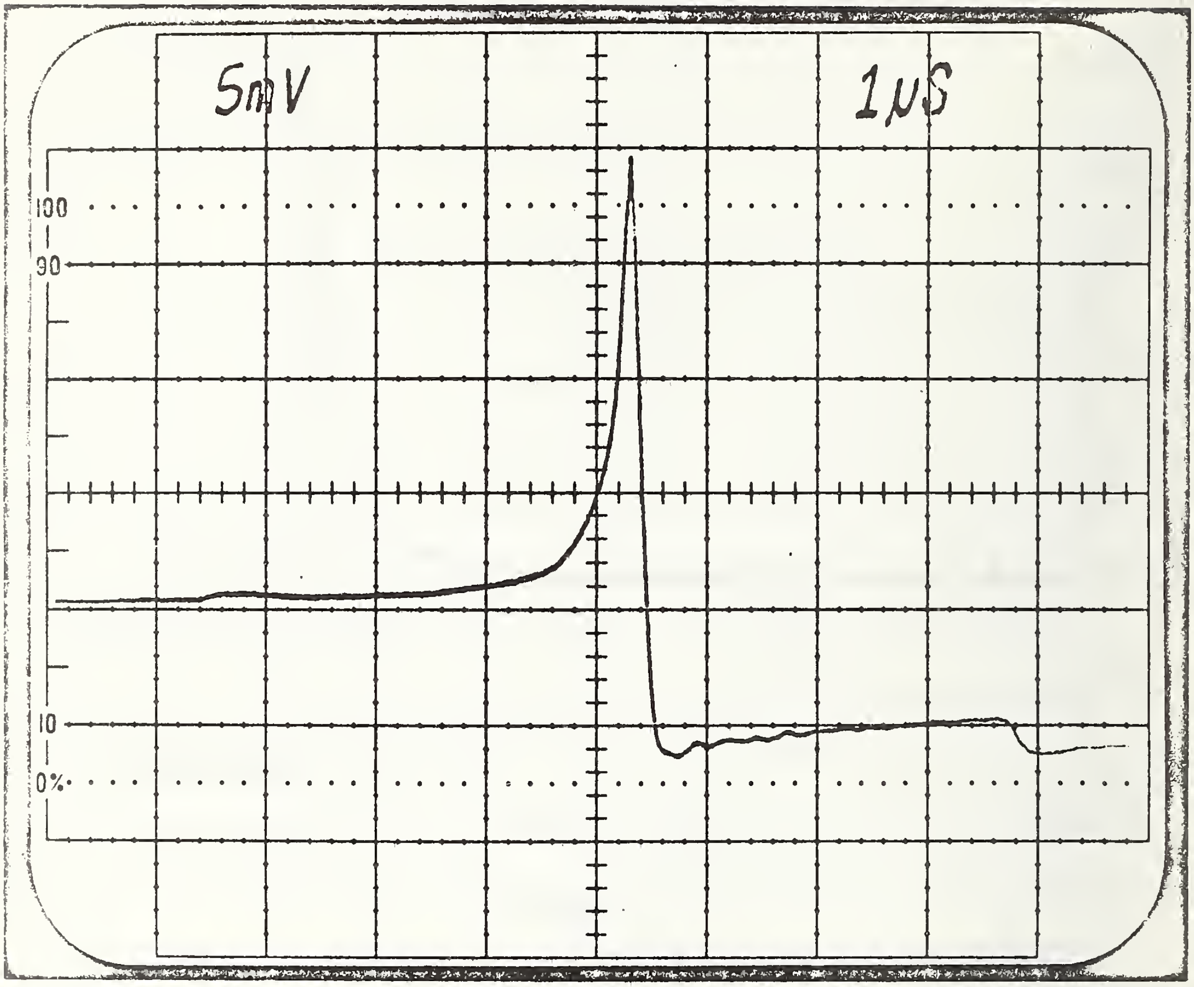

FIG. 3. Oscillogram showing result of a seismic surface pulse experiment on a glass block, ν = 0.226. The block was 3.3 cm thick and all lateral dimensions exceeded 9 cm. Source, breaking of glass capillary 0.15 mm in diameter. Receiver: cylindrical brass electrode 6.3 mm in diameter and 6.3 mm long; air gap, 2 μm; polarization, 20 V. Source to receiver, 2.54 cm. Each division on the abscissa equals 1 μs. Compare with Fig. 2.

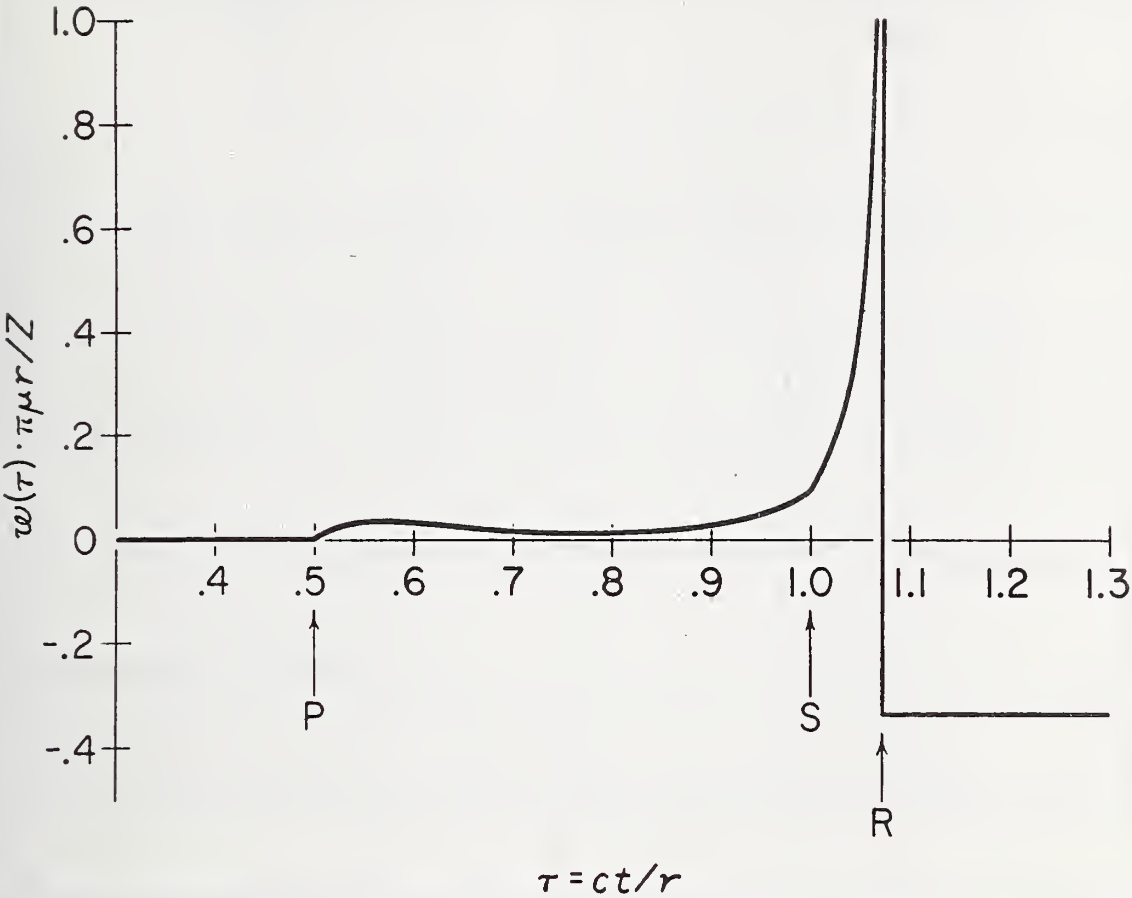

FIG. 4. Same as Fig. 2 but recalculated for ν = 1/3.

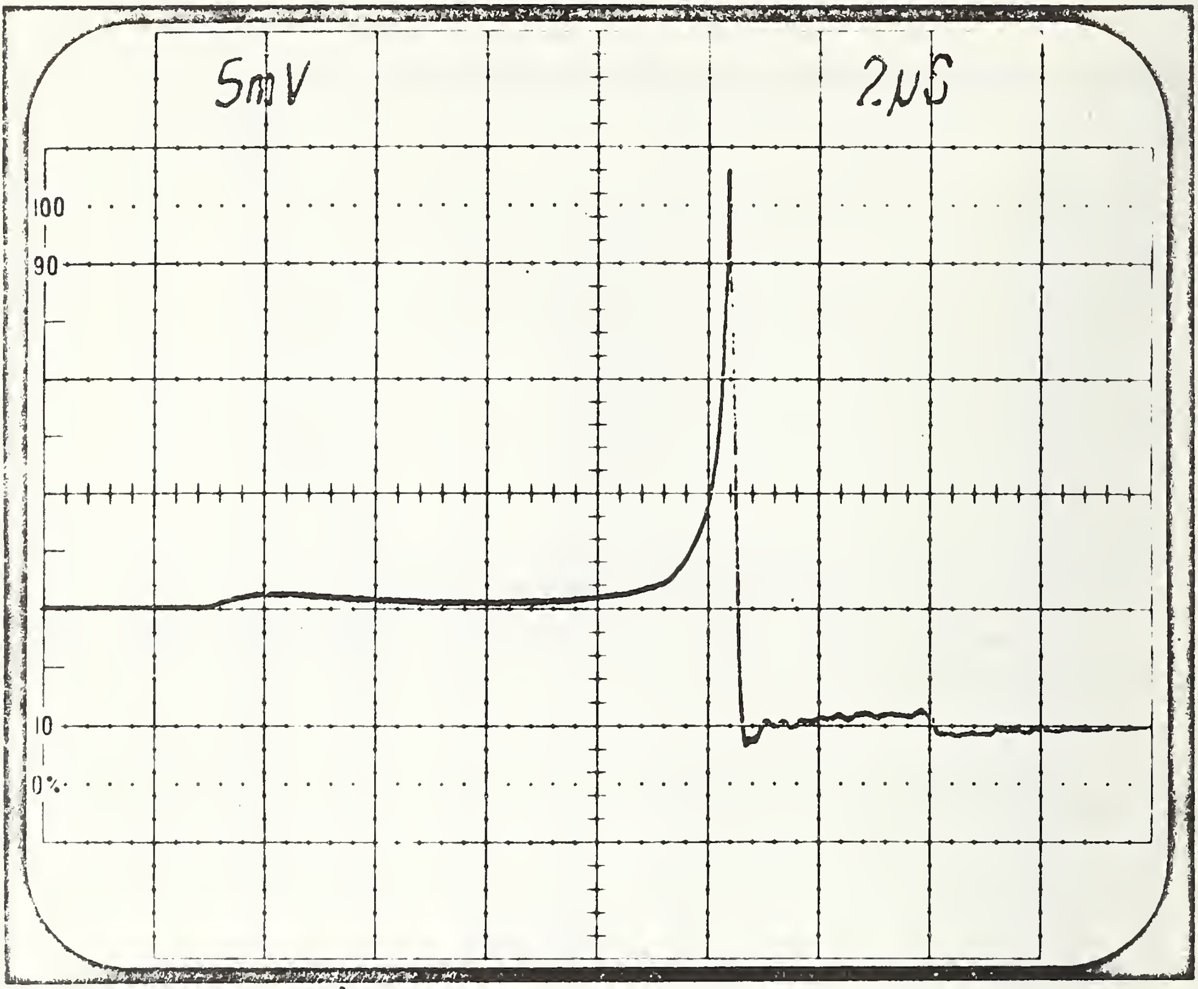

FIG. 5. Same as Fig. 3 but for aluminum-alloy block, $\nu = 0.343$, 6.3 cm thick and 17.8 cm in diameter. Source, breaking of glass capillary 0.15 mm in diameter. Receiver: cylindrical brass electrode 1.27 cm in diameter and 1.27 cm long; air gap, 3.6 μm; polarization, 200 V. Source to receiver, 5.08 cm. Each division on the abscissa equals 2 μs. Compare with Fig. 4.

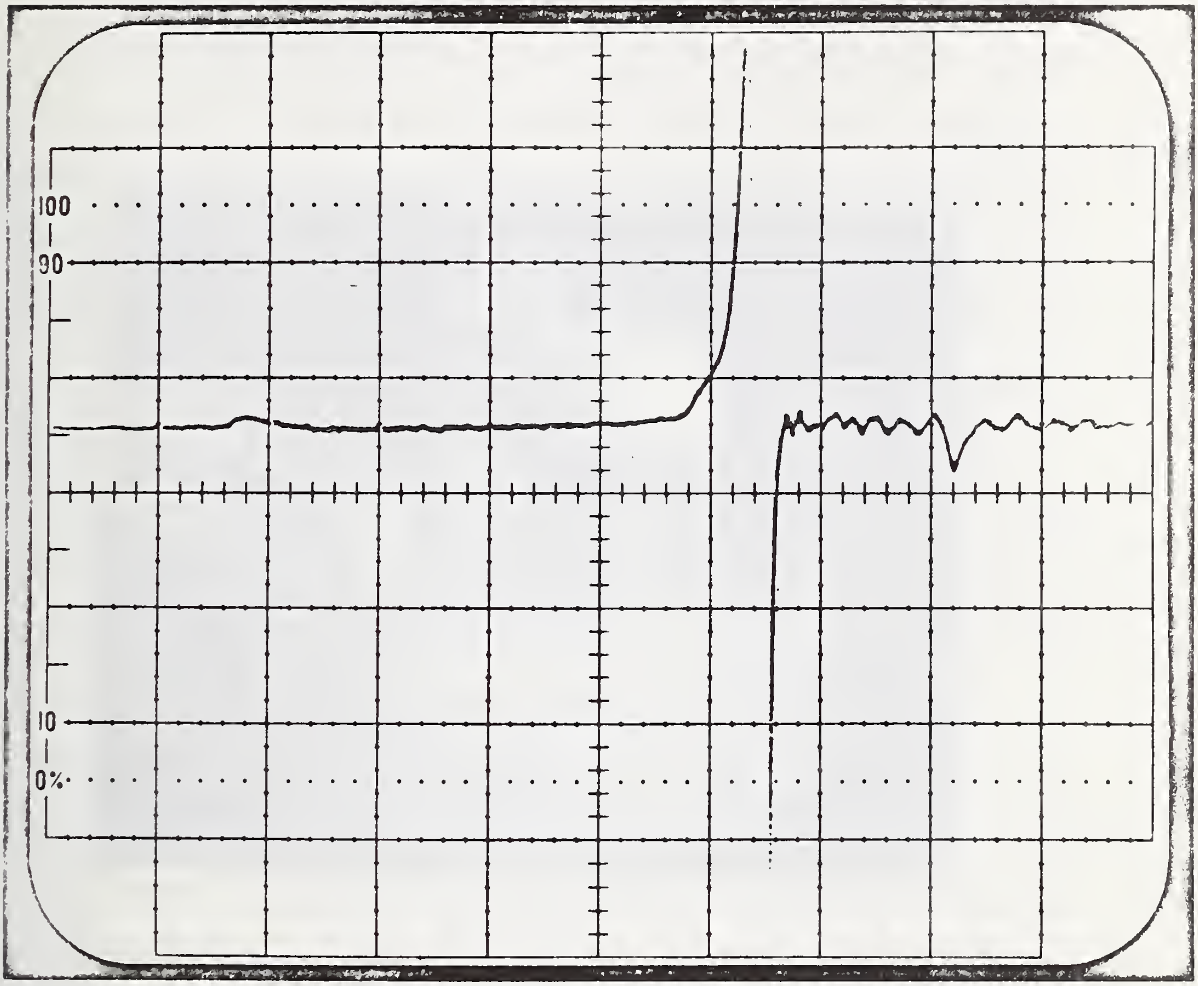

FIG. 6. Oscillogram obtained in experiment similar to that of Fig. 5, but with ordinate proportional to velocity, rather than displacement. Obtained by insertion of true differentiator in amplifier chain. Each division on the abscissa equals 2 μs.

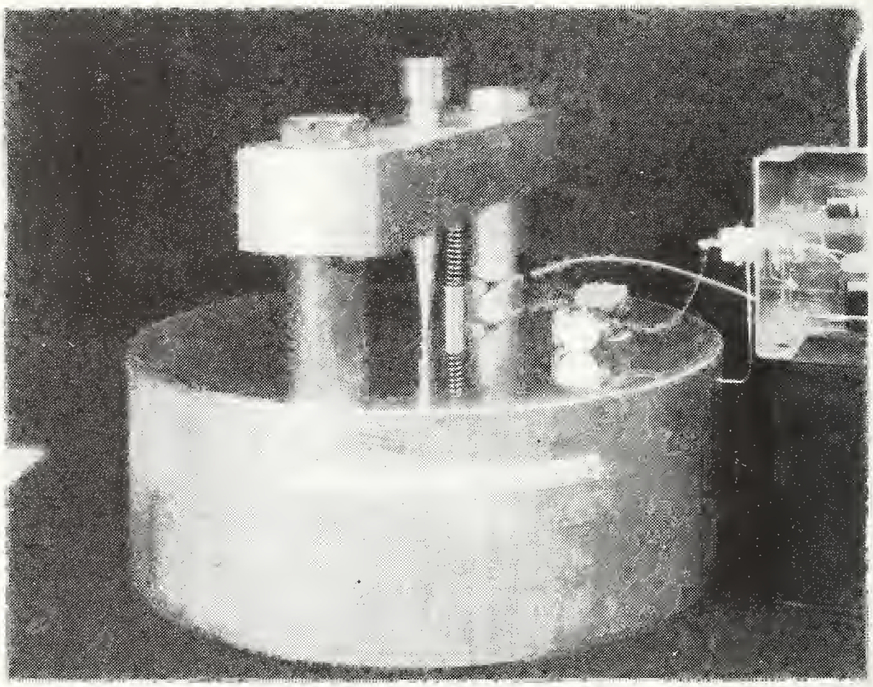

FIG. 7. Photograph of set-up which yielded oscillogram, Fig. 5. The pickup near the indenter provides a signal which triggers a high-speed storage oscilloscope.

were measured using an electrostatic transducer having a cylindrical electrode with axis parallel to the surface of the block and normal to the line from the point of application of the load. Relevant parameters are given in the captions to the figures. The jog near the end of the trace in each of the oscillograms, Figs. 3, 5 and 6, marks the arrival of the first reflection from the back of the block.

Of course, it is difficult to make a quantitative comparison between calculation and experiment when the former leads to an infinite displacement. Nevertheless, the similarity between the two is remarkable. Also we note that the fall time (10 to 90 percent) of the drop corresponding to the arrival of the R-wave, which is zero in the ideal case, is actually only about 0.15 μs. The factors contributing to a finite fall time are (1) finite rise-time of the input (this is the point in question), (2) finite area of application of the load, (3) attenuation in the block,[10] (4) finite size of the receiving transducer, and (5) frequency response of the receiving circuits. Part of (4) above, namely the finite width of the receiver, alone accounts for 0.06 μs in case of the glass and 0.13 μs in case of the aluminum. Thus the rise-time of the step produced by the breaking capillary does not exceed 0.1 μs; it is probably much smaller.

It thus appears that we have at our disposal a standard source (i.e., the breaking glass capillary) the signal from which, as received by the transducer, G (see Fig. 1), can be compared with that gotten on the same transducer from an actual source event in the sample, B.

A QUASI-BURIED PULSE EXPERIMENT

We now have to examine the effect of having the source event located on a surface of a solid instead of within it, as is usually the case. For this purpose we have recourse to another seismological problem, that of the "buried seismic pulse". In this problem, treated first by Lamb[7] and later by others, we have a step-function load source, ZU(t), at a point in the interior of a semi-infinite solid at a distance H below the free plane surface. We can compare the analytical solution of this problem to the experimental results obtained with the transfer block. Pekeris and Lifson[11] give an exact solution for the following case. The free surface is horizontal and the step function of force, vertical. The displacement is calculated for all points (except the epicentral one) on the surface for υ = 1/4. From this solution we have calculated the displacement at the epicentral point (i.e., directly above the load point) for υ = 1/3. The result is shown in Fig. 8. Except for H, the symbols have the same meaning as before. This is to be compared with the oscillogram, Fig. 9, gotten under the conditions given in the caption. The agreement in the general features is altogether remarkable. Two quantitative comparisons are noteworthy. First, the measured rise time is something over 0.1 μs of which some 0.03 μs is owing to the finite diameter of the receiver. Second, the calculated ratio of the displacement at τ = 1.0 to that at τ = 0.5 is 4.38; the experimental value, as nearly as can be read from the oscillogram, is 4.4. It thus appears that there is no important difference between the

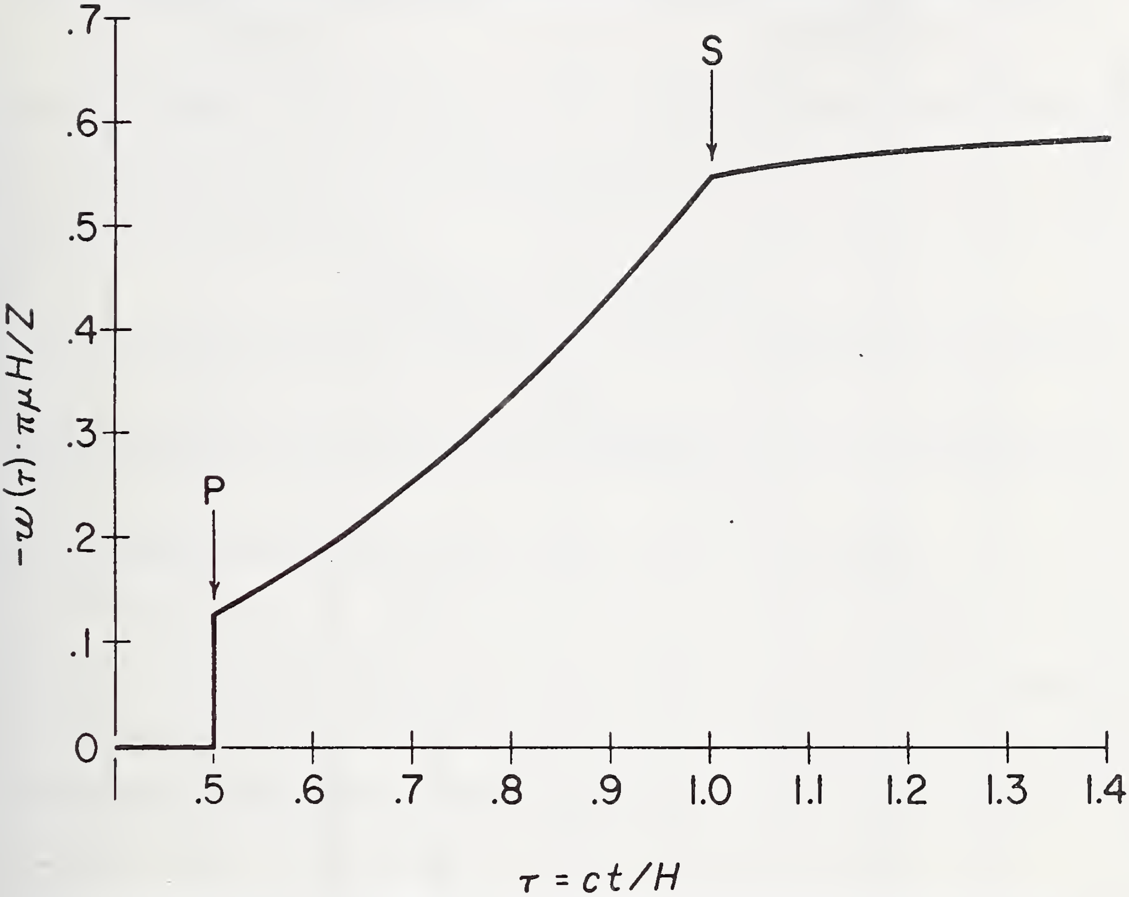

FIG. 8. Vertical displacement for seismic buried pulse calculated from expressions of Pekeris and Lifson[11] for $\nu = 1/3$. P and S show the arrivals of the longitudinal and shear waves, respectively. See text for meaning of symbols.

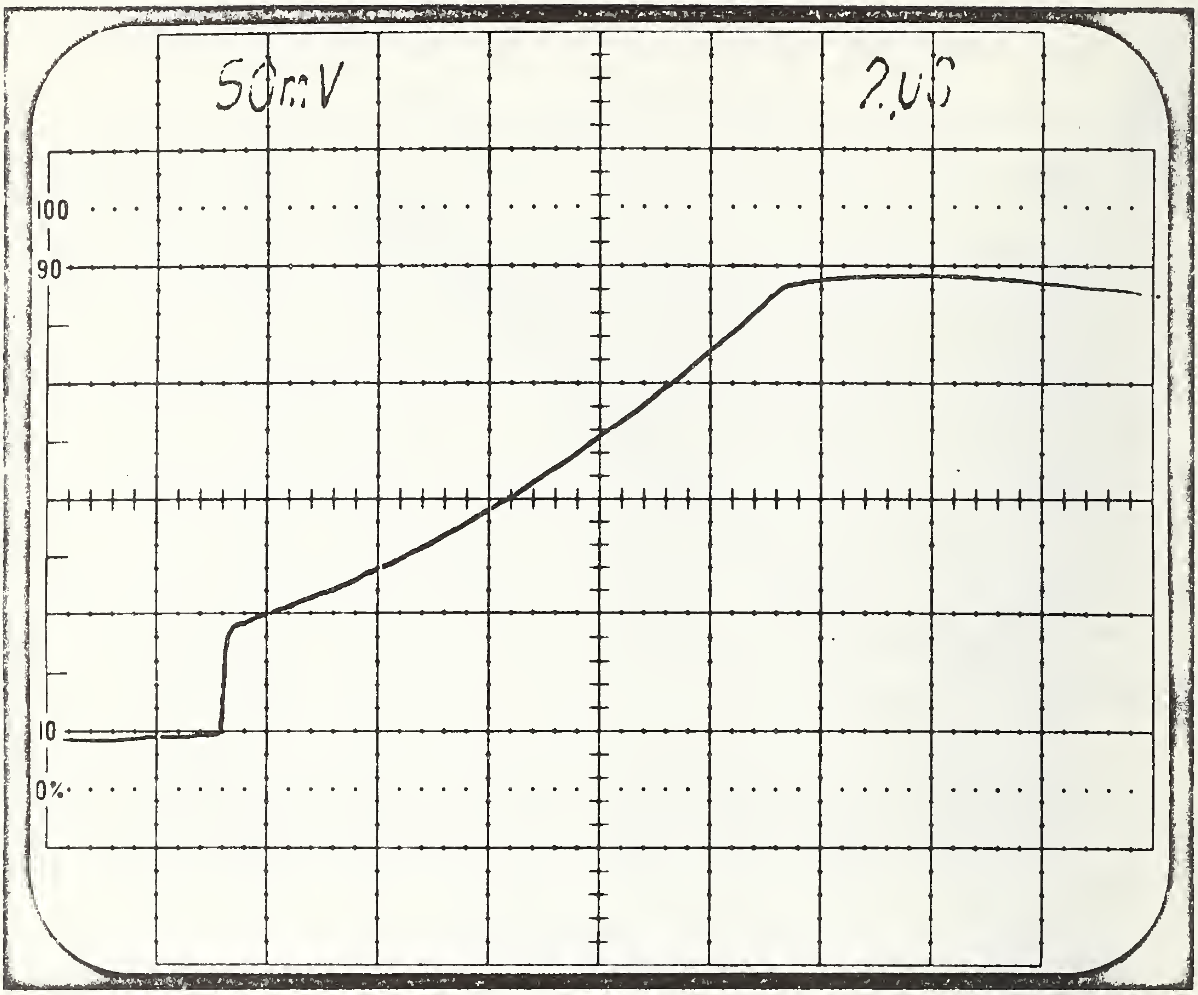

FIG. 9. Oscillogram showing the vertical displacement at a point on one surface of a block resulting from a step of load applied to the other surface directly opposite. The block is the same aluminum-alloy block as in Fig. 5. Source, breaking of glass capillary 0.1 mm in diameter. Receiver: tungsten carbide backplate 9.6 mm in diameter and 2.5 cm long, flat end to; air gap, 4.1 μm; polarization, 200 V. Each division on the abscissa equals 2 μs. Compare with Fig. 8.

vertical displacement at the epicentral point produced by a source event on the surface and that produced by an event in the interior. The oscillogram, Fig. 10, is the same as Fig. 9, except the ordinate is velocity, obtained by differentiation.

CALIBRATION OF TRANSDUCERS

A convenient set-up for the purpose of calibrating a transducer is that of Fig. 1, with the test-sample B replaced by a standard source. The output of the test transducer is then compared with that of a standard transducer. In our work, the latter is an electrostatic one, as already described. The standard source can be any that is reproducible, but the calibration can be obtained only for those frequencies at which the source has adequate output - hence our emphasis on sources of short rise-time. If the source is a one-shot affair, the transducer outputs could be acquired on a transient recorder or the waveforms digitized some other way - in either case the data would be processed off line. We have used a breaking glass capillary for such a source; its output has a reproducible spectrum and the amplitude can be normalized from measured values.

A repetitive source allows the transducer outputs to be processed on line with a conventional spectrum analyzer, the received signal being gated to eliminate reflections. As already indicated, an air-dielectric electrostatic transducer is flat with frequency as a force transmitter. We have constructed one of these using, as an

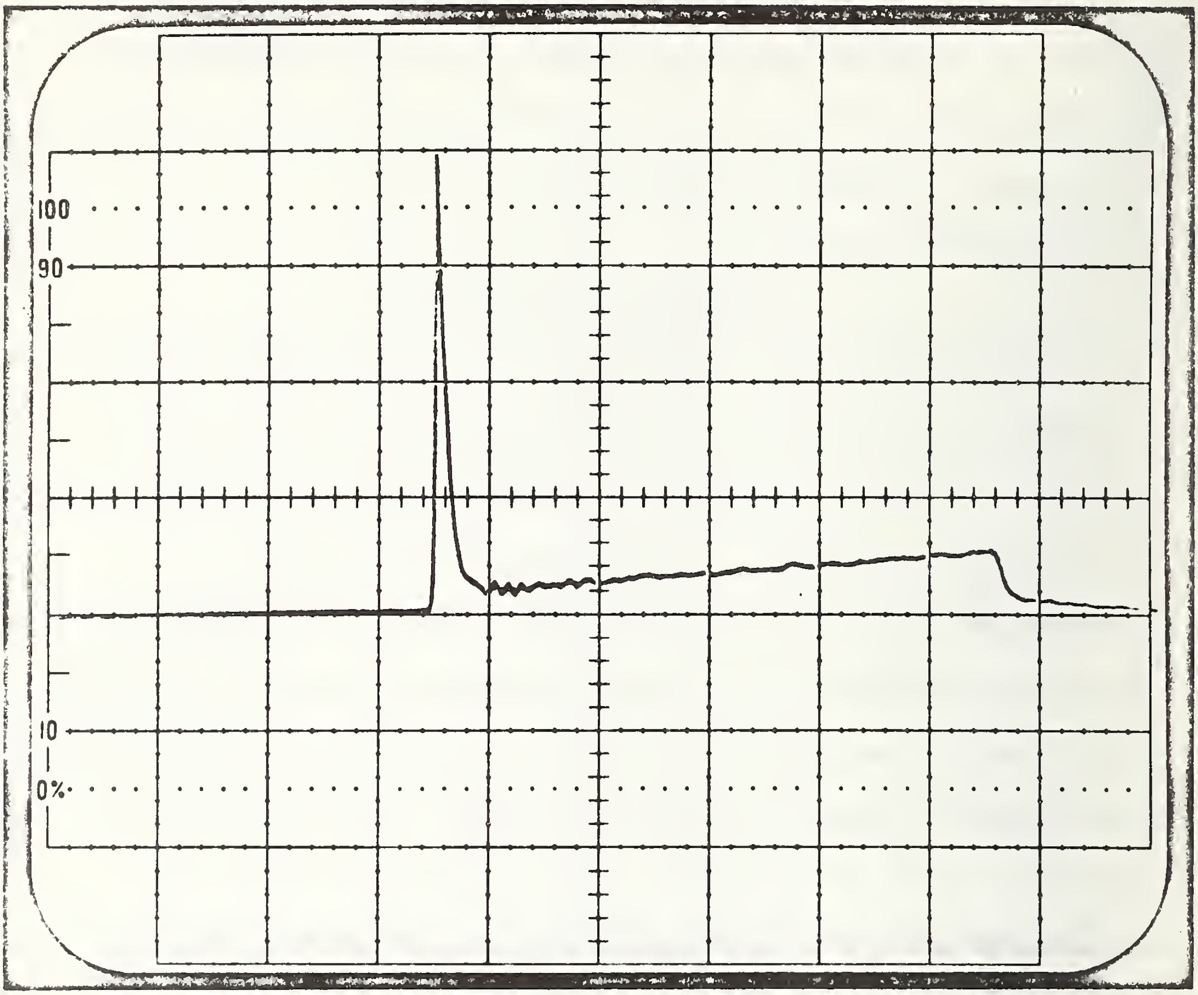

FIG. 10. Oscillogram obtained in an experiment similar to that of Fig. 9, but with ordinate proportional to velocity, rather than displacement. Obtained by insertion of a quasi-differentiator, having a time constant of 0.1 μs, in amplifier chain. Each division on the abscissa equals 2 μs.

outer electrode, a tungsten cylinder of diameter 1 cm and length 0.5 cm having its flat end spaced 4 μm from the surface of the transfer block. This was energized with a 200-V step having a rise time of about 10 ns gotten from an ordinary mercury-wetted relay. As one example, a calibration was run on a 1-MHz wide-band transducer of the type commonly sold for flaw detection. With a pulse repetition rate of 10 to 20 per second, a spectrum covering the range 0-10 MHz was obtained in about 100 seconds. The peaks near (but below) 1, 3 and 5 MHz were rather pronounced. On the other hand, a similar test of a 5-MHz transducer by the same manufacturer revealed a much less pronounced resonance, showing it to be more highly damped than the 1-MHz transducer. For accurate work, these spectra should be compared to that of a standard transducer, because the standard source used applies the force over a large area and the result is not calculable.

Another repetitive source is due to Bell[12,13] who has developed an interesting method for calibration of acoustic-emission transducers based on a spark source. A spark is struck between a needle or ball electrode and the surface of a test block and a signal is picked up by the test transducer at a remote point on the surface of a long bar. The point of view is different from that discussed here. Bell assumes that the mechanical load impressed by the spark is the same as that of an acoustic emission source event; the signature obtained from the transducer is then considered to represent its response to a source event in a typical application. A

repetitive spark is easily got from a simple relaxation oscillator and the output can be processed on line as just described. With our apparatus the time history of the load impressed by such a spark is easily determined. It resembles a step-function deficient in low frequencies - the smaller the spark, the greater the deficiency. The rise is rather fast, but in some cases there is some overshoot. In a later development[14] the spark is drawn between two electrodes near, but not touching, the specimen. In this case, there is again great variability, depending on the parameters. For instance, for a 3 mm gap 3 mm from the surface the rise time is about 5 μs, but for a 1.5 mm gap 1.5 mm from the surface it is about 1 μs. In no case did the spark appear to be either a step- or δ-function source. All of the spark sources we tried had the desirable feature that the results were repeatable once the parameters were fixed.

The (DC-biased) electrostatic force transmitter can also be energized with a short burst, the carrier frequency of which is swept at constant amplitude over the gamut of interest. The received signal, gated to eliminate reflections, is displayed on a storage oscilloscope, the sweep of which is synchronized with that of the oscillator. The result is an amplitude spectrum which corresponds to a δ-function input on the transfer block. This system has the advantage that it does not call for a spectrum analyzer. With it we have calibrated a number of commercial wide-band transducers. Two nominally identical 1-MHz units proved to be nearly matched in

sensitivity but not so well matched in frequency response. Of four nominally identical 5-MHz transducers, the least sensitive had half the sensitivity of the most sensitive. Similar results were obtained for 10- and 15-MHz transducers.

In all of the above, we have calibrated transducers as receivers. The same apparatus could be used to calibrate them as transmitters.

CONCLUSION

We have described some apparatus with which we hope to obtain signatures of numerous acoustic-emission source events produced by both plastic deformation and temperature-induced phase changes. For very energetic source events, electrostatic receiving transducers will be preferred because of their very large bandwidth. For lesser events, it may be necessary to use wide-band piezoelectric transducers, perhaps several covering different ranges of frequency for each type of event. No doubt there are also source events so feeble that they cannot be detected with wide-band transducers at all; these will have to be ignored for the present. The apparatus has proved to be useful for the "calibration" of transducers. In particular, it becomes very easy to detect variations in sensitivity and frequency response and to ascertain the effects of changes in clamping force and couplant on response. Finally, we believe some of our results will be of interest to seismologists and elasticians.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A method for obtaining the signatures (waveforms) of certain acoustic emission events has been developed. The waveform is that at the source, free of contamination by ringing of the specimen, apparatus and transducer. The technique is based on the comparison of two signals at the transducer, one from the event in question and one from an artificial event of known waveform. The apparatus is also adapted to the calibration of transducers in a certain sense. The configurations of source (real or simulated acoustic-emission event) and receiving transducer correspond to those of some special cases of Lamb's problem. As a byproduct, the results may be of some interest to seismologists.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Acoustic emission; calibration of transducers; electrostatic transducers; Lamb's problem; seismic pulses; ultrasonic transducers.

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